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1 Attorney Docket No. 84493

2

3 **METHOD FOR DETERMINING LOCAL INNER AND OUTER**

4 **BOUNDARY LAYER LENGTH SCALES FROM DRAG MEASUREMENTS**

5 **IN HIGH REYNOLDS NUMBER TURBULENT FLOWS**

6

7 **STATEMENT OF GOVERNMENT INTEREST**

8   The invention described herein may be manufactured and used

9 by or for the Government of the United States of America for

10 governmental purposes without the payment of any royalties

11 thereon or therefore.

12

13 **BACKGROUND OF THE INVENTION**

14 1. Field of the Invention

15   The present invention generally relates to the estimation

16 of the flow noise on a cylindrical body in a turbulent flow and,

17 more particularly, to a method for determining inner and outer

18 boundary layer length scales from a succession of drag

19 measurements of a long thin cylindrical body in any fluid as a

20 precursor to estimating flow noise.

21 2. Description of the Prior Art

22   There is a significant practical need to know the drag and

23 flow noise of towed long thin cylindrical bodies. The need

1   arises in a variety of contexts including torpedoes and towed

2   sonar arrays.

3   Towed sonar arrays are sonar systems that are designed to

4   be towed by a submarine or a surface vessel in order to detect

5   other submarines. The arrays are typically long, hose-like

6   structures measuring up to a thousand feet or longer that

7   contain specially designed acoustic sensors, called hydrophones,

8   which receive acoustic waves . The arrays include electronics

9   that convert the acoustical waves from analog to digital form

10   and transmit that data to electronic processors on board the

11   towing vessel.

12   The processor must distinguish radiated sound from other

13   submarines from ambient and self noise, which includes the flow

14   noise of the towed array. Thus, it is important to accurately

15   estimate flow noise in advance, for design purposes. Moreover,

16   towed arrays must be designed to withstand the extreme

17   environmental stresses of operation in the ocean depths, and so

18   it is necessary to accurately estimate drag, and estimate the

19   local wall shear stress as well. Accomplishing this requires an

20   understanding of the turbulent boundary layers which exist on

21   the arrays.

22   The inner region of the boundary layer is dominated by

23   viscous effects, and the outer region is dominated by inertial

24   effects. Two dimensional flat plate turbulent boundary layers

1 have been explored thoroughly for several decades, and it is

2 generally accepted that the (inner) viscous length scale and the

3 (outer) boundary layer momentum thickness scale adequately

4 characterize the flow.

5   Most practical engineering flows, however, are

6 characterized as high-Reynolds number flows. Since the viscous

7 length scale decreases rapidly with increasing Reynolds number,

8 and the outer length scales are only a weak function of Reynolds

9 number, the inner and outer scales become increasingly disparate

10 with increasing Reynolds number. Thus, more complex turbulent

11 flows are often not well described by the Reynolds number alone,

12 and must be described using inner and outer boundary layer

13 length scales.

14   In the context of a towed array, the hydrodynamic flow is

15 a high Reynolds number turbulent boundary layer, which may be

16 equilibrium or nonequilibrium depending on the ship motion.

17 Consequently, it is necessary to know the inner and outer

18 boundary layer length scales, which characterize the flow field,

19 for estimation of flow noise on long thin cylinders, and in

20 particular, current and next generation towed sonar arrays.

21   Currently there are no viable approaches for determining

22 the inner and outer boundary layer length scales in tow tank

23 testing or full scale sea trials. Laser Doppler Velocimetry

24 (LDV) and Particle Image Velocimetry (PIV) have been used

1 extensively for measurements of turbulence in laboratories.

2 However, oceanic field applications are impractical. It would

3 be greatly advantageous to provide a method for determining

4 inner and outer boundary layer length scales and, more

5 particularly, from a succession of drag measurements of a long

6 thin cylindrical body, in order to estimate flow noise and for

7 improved computational modeling of the dynamics of towed arrays

8 in water or other towed bodies in air.

9

SUMMARY OF THE INVENTION

11   Accordingly, it is an object of the present invention to

12 provide a method for determining inner and outer boundary layer

13 length scales.

14   It is another object of the present invention to provide a

15 method for determining inner and outer boundary layer length

16 scales from a succession of drag measurements of a long thin

17 cylindrical body.

18   It is still another object of the present invention to

19 provide a method for determining inner and outer boundary layer

20 length scales of a long thin cylindrical body in order to

21 estimate flow noise and for improved computational modeling of

22 the dynamics of towed arrays in water.

23   In accordance with the stated objects, a method is provided

24 for determining the local inner and outer turbulent boundary

4

1 layer length scales from experimental measurements of the drag

2 on a long thin cylindrical body at low or high momentum

3 thickness Reynolds numbers. A succession of measurements of the

4 total drag on a cylinder under tow is taken for particular

5 conditions (flow speed, fluid density, fluid viscosity,

6 cylindrical body geometry). After each measurement the cylinder

7 is truncated by a fixed amount, and the process is repeated for

8 the entire length of the cylinder. The collective measurements

9 provide a spatially and temporally averaged measure of the mean

10 wall shear stress and momentum thickness, from which the inner

11 and outer length scales can be determined directly, for each

12 separate segment of the cylinder. The inner and outer boundary

13 layer length scales may then be used for estimation of flow

14 noise on long thin cylinders, and in particular, current and

15 next generation towed sonar arrays. In particular, this method

16 also allows the spatial variation of the length scales down the

17 length of the cylinder to be determined directly.

18   The present invention reduces the time and overhead

19 required to produce the accurate flow data needed for proper

20 engineering of towed sonar arrays.

BRIEF DESCRIPTION OF THE DRAWINGS

1

2   FIG. 1 is a schematic drawing illustrating the towing

3 configuration and load cell used in accordance with the present

4 method;

5   FIG. 2 is a diagram of the control volume for cylindrical

6 coordinates based on a side view of a tested cylinder; and

7   FIG. 3 is an end view of the control volume for cylindrical

8 coordinates from the view of reference line 3-3 of FIG.2.

9

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

11   The present invention is a method for determining inner and

12 outer boundary layer length scales from a succession of drag

13 measurements of a long thin cylindrical body in any fluid as a

14 precursor to estimating drag and flow noise.

15 The methodology begins by towing a unit under test (UUT),

16 preferably a long thin neutrally buoyant cylinder 10, in a

17 controlled environment such as a towing tank, or from a surface

18 platform under conditions for which the ambient flow field is

19 known.

20   FIG. 1 is a schematic drawing illustrating the requisite

21 towing configuration, which includes a movable vehicle capable

22 of towing the UUT 10. The vehicle may be any air or sea vessel

23 or, as illustrated in FIG. 1, a movable tow platform 12 capable

24 of towing the UUT 10 in the illustrated tow direction "A"

1 through a fluid medium 40 (here illustrated as water). In the

2 illustrated embodiment the tow carriage 12 is mounted over a tow

3 tank. A processor 14 such as a conventional laptop computer is

4 supplied, here on the tow carriage 12, and is coupled for data

5 transmission (by RS-232, USB port or otherwise) to a load cell

6 computer interface 16. One skilled in the art will recognize

7 that the processor 14 may be any suitable computer located on-

8 site or in remote communication with the load cell computer

9 interface 16.

10 The load cell computer interface 16 may be a conventional

11 multi-meter as will be described or any other interface capable

12 of digitizing the analog voltage signal produced by a load cell

13 22. A conventional fixed tow strut 18 extends beneath the tow

14 carriage 12 into the fluid medium 40. The load cell 22 is

15 mounted distally on the tow strut 18 behind a common fairing 24

16 which minimizes the generation of turbulence. The load cell 22

17 may be any common type of tensile load measuring device, such as

18 a strain gage load cell. An axial type load cell usually

19 consists of a hollow or solid cylindrical shaft and four strain

20 gages mounted around the circumference.

21 The strain gages are mounted and connected to form a

22 Wheatstone bridge circuit. The load cell 22 is tethered by a

23 leader line 26 to the UUT 10, which is depicted as a small

1   diameter cylinder. The leader line 26 separates the UUT 10 from

2   any turbulence generated by the tow strut 18.

3   In practicing the method of the invention, the UUT 10 is

4   towed and the total drag on the towed cylinder is measured

5   directly by the load cell 22, which outputs an analog signal

6   that is digitized by the load cell computer interface 16. The

7   digitized load is processed using a control volume analysis

8   extended to the case of axisymmetric flows to exactly calculate

9   the momentum thickness (which is the outer length scale) of the

10   turbulent boundary layer at the end of the cylinder UUT 10.

11   A suitable control volume analysis is detailed below in

12   reference to FIGS. 2 and 3. This calculation requires the angle

13   of tow of the UUT 10 to be within one degree, and the tow speed

14   U_o to be steady temporally.

15   Next, a fixed-length segment of the UUT 10 is removed from

16   its trailing end, and the total drag on the towed cylinder is

17   measured directly as described above by the load cell 22, and

18   the control volume analysis of axisymmetric flow is repeated to

19   calculate the momentum thickness of the truncated cylinder UUT.

20   The foregoing procedure is repeated successively, with a

21   fixed segment of the cylinder UUT 10 being removed for each drag

22   measurement. A typical UUT segment length to remove is

23   approximately 1 m, but could be larger or smaller, depending on

1 the desired spatial resolution. The foregoing procedure is

2 repeated for the entire length of the UUT 10.

3   It can be seen that the difference in drag between

4 consecutive measurements yields the spatially and temporally

5 averaged mean wall shear that exists on each particular segment.

6 By repeating this procedure over the entire length of the UUT

7 10, the spatial dependence of the mean wall shear stress is

8 determined, as well as the spatial dependence of the momentum

9 thickness.

10   FIG. 2 is a diagram of the control volume for cylindrical

11 coordinates. A standard control volume analysis is applied in

12 which the following notations are used.

13   a cylinder radius (ft)

14          $u(r)$ temporal mean streamwise velocity at radial

15   location r (ft/sec)

16   r radial distance from the center of the cylinder

17   (ft)

18   x streamwise distance from the leading edge of the

19   cylinder (ft)

20   U_o tow speed of the cylinder (ft/sec)

21   CS   control surface of the control volume (ft^2)

22   dA   incremental annular surface area at the end of

23   the control volume (ft^2)

1     $\overline{F}$ vector force applied to the surface of the

2   control volume (lbf)

3   F streamwise scalar force applied to the surface of

4   the control volume (lbf)

5   A_s total surface area of the cylinder (ft^2)

6   A_2 annular surface area at the end of the control

7   volume (ft^2)

8   L length of the cylinder (ft)

9   C_d tangential drag coefficient (nondimensional)

10   s boundary layer inner length scale (ft)

11   ν kinematic viscosity of the fluid (ft^2/sec)

12   μ_τ friction velocity (ft/sec)

13   τ_w temporally averaged mean wall shear stress (psf)

14   τ_{ave} spatially and temporally averaged mean wall shear

15   stress (psf)

16   ρ fluid density (slugs/ft^3)

17   δ boundary layer thickness at the end of the

18   cylinder (ft)

19   boundary layer momentum thickness at the end of the

20   cylinder (ft)

21     $\overline{V}$ temporal mean velocity vector (ft/sec)

22   d connotes the derivative of the associated term

1   The outer boundary layer length scale is the momentum

2   thickness 100 itself, and the inner boundary layer length scale

3   is given by v/μ_τ , where $\mu_\tau = (\tau_w/\rho)^{1/2}$.

4   Using cylindrical coordinates, as shown in FIGS. 2 and 3,

5   an expression for the momentum thickness 100 is derived. For

6   convenience, the radius of the cylindrical control volume is

7   chosen to be equal to the value of the boundary layer thickness δ

8   at the end of the cylinder, and the length is the total length

9   of the cylinder or UUT 10. The origin is the centerline 120 of

10   the cylinder, such that the surface of the cylinder is at r = a.

11   In the following analysis, all quantities represent the temporal

12   mean values. We first present an expression defining the

13   momentum thickness θ for this case. Equating the momentum flux

14   through an annulus in the free stream, to the momentum flux

15   defect in the boundary layer, leads to

16
$$\theta^2 + 2a\theta = 2\int_a^{\delta+a} \frac{u(r)}{U_o}\left(1 - \frac{u(r)}{U_o}\right)r\,dr \qquad (1)$$

17   which again can only be evaluated for θ if u(r) the mean

18   streamwise velocity in the boundary layer is known. However,

19   the momentum thickness may also be derived using a control

20   volume analysis. A cylindrical control volume is used, as shown

21   in FIG. 2, and steady-state conditions are imposed.

22   Conservation of mass for the control volume yields

$$\int_{CS} \rho \overline{V}(r, \theta, x) \cdot d\overline{A} = 0 \qquad (2)$$

where vector $\overline{V}$ is the temporal mean velocity at the location of the control volume surfaces. Conservation of momentum applied to the control volume can be written as

$$\int_{CS} \overline{V} \rho \overline{V} \cdot d\overline{A} = \sum \overline{F} \qquad (3)$$

Note that the only applied force $\overline{F}$ on the cylindrical control volume of fluid is the shear force at the wall of the cylinder. This force is equal to the streamwise component of the mean wall shear stress averaged over the surface area of the entire cylinder multiplied by the total surface area $A_s = 2\pi aL$. Evaluating the integral at each control surface, and making use of equation (2), yields

$$\frac{\tau_{ave} A_s}{\rho U_o^2} = \int_{A_2} \frac{u(r)}{U_o}\left(1 - \frac{u(r)}{U_o}\right) dA \qquad (4)$$

where $dA = r dr d\theta$. The quantity τ_{ave} which is inferred from the drag measurements, is related to the spatially varying wall shear stress through the relation

$$\tau_{ave} = \frac{1}{L}\int_0^L \tau_w(x) dx \qquad (5)$$

12

1 Equation (4) can be simplified to

$$\frac{\tau_{ave}}{\rho U_o^2} = \frac{1}{L} \int_a^{a+\delta} \frac{u(r)}{U_o}\left(1 - \frac{u(r)}{U_o}\right)\frac{r}{a}dr = \frac{1}{2}C_d \qquad (6)$$

2

3 where C_d is the total tangential drag coefficient over the

4 cylinder length L.

5 Thus, from the measured quantity C_d, equation (6) can be solved

6 for the temporally and spatially averaged mean wall shear stress

7 τ_{ave} existing on each segment of the cylindrical body. From τ_{ave},

8 the inner boundary layer length scale s can be directly

9 determined.

10 Using equation (1) for the definition of momentum thickness

11 in conjunction with the control volume analysis, the following

12 relationship is obtained between θ evaluated at x = L and C_d for

13 the case of a cylinder in a steady, uniform flow:

$$\theta^2 + 2a\theta - aLC_d = 0 \qquad (7)$$

14

15 The outer boundary layer length scale is the momentum

16 thickness θ itself, which is determined directly from equation

17 (7), with the measured value of C_d known.

18 Thus, we now have an accurate determination of the inner

19 and outer boundary layer length scales s and θ (the inner viscous

20 length scale and the outer boundary layer momentum thickness

21 scale), which are generally recognized as adequately

1 characterizing the flow. The calculations are derived very

2 simply from a succession of drag measurements of a long thin

3 cylindrical body. The calculations may then be used for the

4 estimation of flow noise and improved computational modeling of

5 the dynamics of towed bodies in fluids such as air or water.

6 This greatly reduces the time and overhead required to produce

7 the accurate flow data needed for proper engineering of towed

8 sonar arrays.

9   Having now fully set forth the preferred embodiments and

10 certain modifications of the concept underlying the present

11 invention, various other embodiments as well as certain

12 variations and modifications of the embodiments herein shown and

13 described will obviously occur to those skilled in the art upon

14 becoming familiar with said underlying concept. It is to be

15 understood, therefore, that the invention may be practiced

16 otherwise than as specifically set forth in the following

17 claims.

1   Attorney Docket No. 84493

2

3   **METHOD FOR DETERMINING LOCAL INNER AND OUTER**

4   **BOUNDARY LAYER LENGTH SCALES FROM DRAG MEASUREMENTS**

5   **IN HIGH REYNOLDS NUMBER TURBULENT FLOWS**

6

7   **ABSTRACT OF THE DISCLOSURE**

8   A method is presented for determining inner and outer

9   boundary layer length scales from a succession of drag

10   measurements of a cylindrical body in order to estimate flow

11   noise and for computational modeling of the dynamics of towed

12   arrays in a fluid medium. A succession of measurements of the

13   total drag on a cylinder under tow at uniform known conditions

14   (flow speed, fluid density, fluid viscosity, cylindrical body

15   geometry) is taken. After each measurement, the cylinder is

16   truncated by a fixed amount, and the process is repeated for the

17   length of the cylinder. The measurements provide a spatially

18   and temporally averaged measure of the mean wall shear stress

19   and momentum thickness, from which the inner and outer length

20   scales can be determined. The inner and outer boundary layer

21   length scales may then be used for estimation of flow noise on
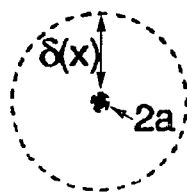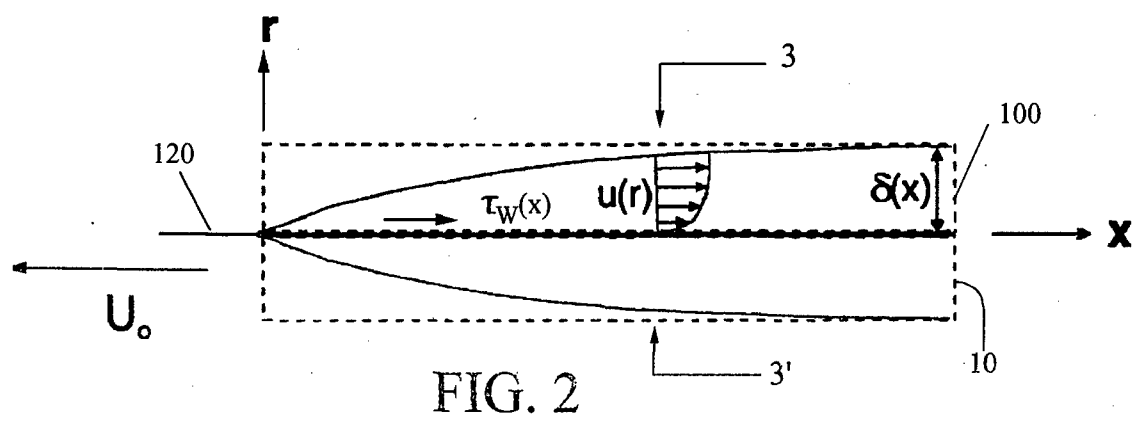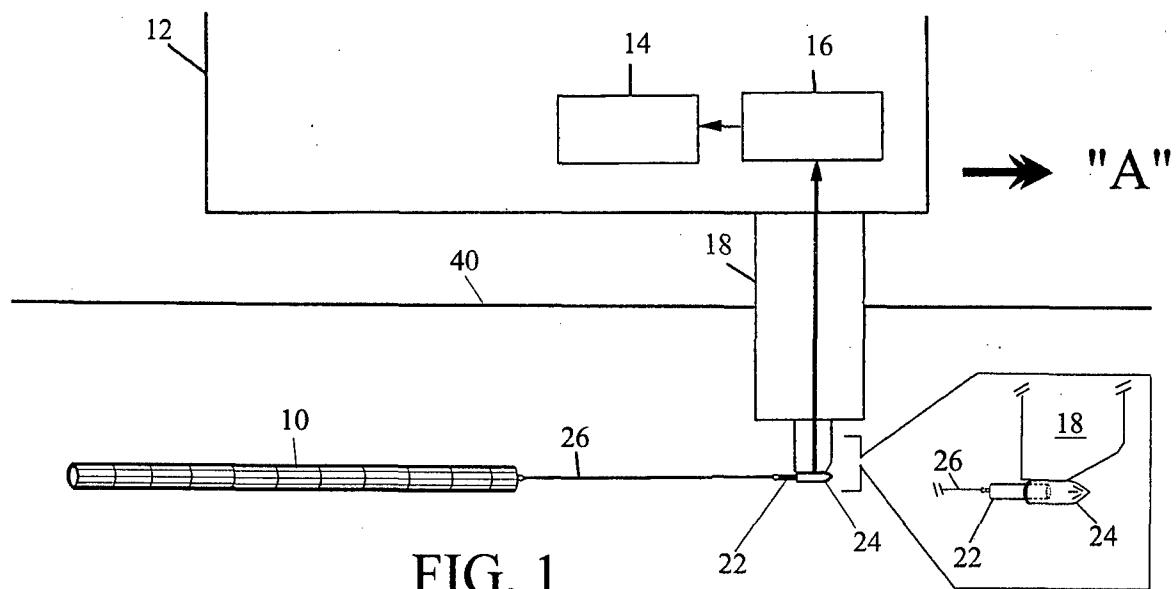
22   towed cylindrical bodies and arrays.

FIG. 1

FIG. 2

FIG. 3